

# LNG as a potential alternative fuel - safety and security of storage facilities

A. Bernatik<sup>a,\*</sup>, P. Senovsky<sup>a</sup>, M. Pitt<sup>b</sup>

<sup>a</sup>VSB – Technical University of Ostrava, Faculty of Safety Engineering  
Lumirova 13, Ostrava-Vyskovice, 700 30, Czech Republic,  
tel: +420 597 322 833, fax: +420 597 322 982, e-mail: [ales.bernatik@vsb.cz](mailto:ales.bernatik@vsb.cz)

<sup>b</sup>University of Sheffield, Department of Chemical and Process Engineering,  
Mappin Street, Sheffield S1 3JD, United Kingdom

## Abstract

The aim of this article is to summarize the safety and security aspects of storing of Liquefied Natural Gas (LNG) as a potential alternative fuel. The contribution deals with possible scenarios of accidents associated with LNG storage facilities and with a methodology for the assessment of vulnerability of such facilities. The protection of LNG storage facilities as element of critical infrastructure should also be a matter of interest to the state. The study presents the results of determination of hazardous zones around LNG facilities in the event of various sorts of release. For calculations, the programs ALOHA, EFFECTS and TerEx were used and results obtained were compared. Scenarios modelled within this study represent a possible approach to the preliminary assessment of risk that should be verified by more detailed modelling (CFD). These scenarios can also be used for a quick estimation of areas endangered by an incident or accident. The results of modelling of the hazardous zones contribute to a reduction in risk of major accidents associated with these potential alternative energy sources.

Keywords: LNG, alternative fuels, hazardous materials, dispersion modelling

## 1. Introduction

Liquefied Natural Gas (henceforth referred to as LNG) is a mixture composed mostly of methane and a small quantity of ethane, propane, nitrogen and other minor components depending on the source of natural gas. The boiling temperature typically ranges from -166°C to -157°C at atmospheric pressure, and the density is in the range from 470 to 430 kg.m<sup>-3</sup>, both depending on the exact composition.

The natural gas in liquid form takes up to 600 times less space than in its gaseous state, which makes it advantageous for tank storage in areas where gas pipelines do not exist. It is commonly kept as a liquid at its boiling point by a combination of higher pressures and lower temperatures than ambient, usually in the range 8 to 12 barg, (~ -25°C to -20°C) in horizontal or vertical insulated vessels of a volumes varying from 20 to 700 m<sup>3</sup>. The tanks are generally of a double-jacketed design in which the inner jacket is made of stainless austenitic steel and the outer one of carbon steel. The space between these jackets is filled with perlite and the jackets are under vacuum, which ensures high quality insulation. The maximum stored LNG volume should not exceed 90% of net tank volume. The tanks are filled from supply ships or road transport tanks by austenitic steel flexible hoses.

For use, the LNG is vaporised and warmed to a temperature of about 5°C then fed to piping at a pressure of 2 to 6 barg. It may be transported as a compressed gas in road tankers or used as fuel in ships. The hazards of this and other gases in transport have been reported previously (Bernatik et al., 2008).

In the past, the relatively low demand for natural gas storage made it possible to locate such installations away from densely populated or intensively utilised areas. However, there are obvious advantages in bringing storage close to the point of use, and the presence of LNG storage may attract industry and hence people to the vicinity. The possible hazards of storage facilities need to be considered by planners and others.

## 2. LNG Hazards

Natural gas is not toxic, but LNG is hazardous because of its temperature, the possibility of asphyxiation and of course the fire risk. These will be dealt with in turn.

If people come in direct contact with the liquid or its containment material, cryogenic burns resembling frostbite can occur. Vapour or cold gas inhalation for a prolonged period can damage lungs. The viscosity of cryogenic liquids is low; this means that they penetrate through porous materials of clothing more quickly than liquids such as water. LNG is also able to cause the embrittlement of materials, such as carbon steel and rubber, and thus contribute to cracking failures.

While a release is often initially visible as a cloud due to the formation of frost from the atmosphere, as the gas warms up it becomes colourless and odourless and thus undetectable to human senses. It is thus easy to enter a region where the oxygen concentration is so low as to cause almost immediate unconsciousness. (It is the

presence of carbon dioxide which causes the symptoms of stuffiness – the absence of oxygen is not detected by the body.)

Obviously, as a fuel gas, it is highly flammable with a lower flammable limit (LFL) of 4 to 5% by volume in air and an upper flammable limit (UFL) of about 15%, depending on temperature.

### 3. Modelling of release and dispersion

A whole series of studies and field experiments (see Table 1) dealing with hazards associated with LNG use have been published. From these the following conclusions may be drawn. The main hazard of LNG spill into the free space above ground is a flash fire; above water then a physical explosion is possible. A vapour cloud explosion (VCE) can occur only exceptionally in confined spaces (the so-called overfilled zone). A BLEVE type explosion seems generally improbable in insulated LNG installations, although it occurred in the case of tanker truck accident in Spain in the year 2002 (Planas-Cuchi et al., 2004).

**Table 1**

Overview of existing LNG spill experiments (SNL, 2004)

EXPERIMENT	SPILL SIZE [m <sup>3</sup> ]	SPILL RATE [m <sup>3</sup> .min <sup>-1</sup> ]	POOL RADIUS [m]	DOWNWIND DISTANCE TO LFL (Max) [m]
ESSO	0.8 – 10.8	9 – 17.5	7 – 17	400
U.S. CC	3 – 5.5	1.2 – 6.6	~ 7.5	-
Maplin Sands (dispersion tests)	5 – 20	1.5 – 4	~ 10	190 ± 20
Maplin Sands (combustion tests)	10.35	4.7	~ 15	-
Avocet (LLNL)	4.2 – 4.52	4	6.82 – 7.22	220
Burro (LLNJ)	24 – 39	11.3 – 18.4	~ 5	420
Coyote (LLNL)	8 – 28	14 – 19	-	310
Falcon (LLNJ)	20.6 – 66.4	8.7 – 30.3	-	380

In the case of damage to a pressure vessel or pipe, a two-phase LNG spill must be considered, and at the beginning of dispersion, a large part of the release will form an aerosol in a cloud of vapour. Although methane at ambient is less dense than air, the low temperature of LNG vapour means that the dispersing cloud will behave as heavy gas and will often form visible white fog. (At air humidity higher than 55%, the cloud of vapours will be visible in the range from lower flammability limit (LFL) to upper flammability limit (UFL); at lower humidity the cloud of vapours in flammable concentrations can be invisible (Raj, 2006)).

For hazardous zone calculations, it is possible to follow the recommendations of recognized methodologies, above all the Dutch publication “Purple Book CPR 18E” (Purple Book, 1999) or the international project “ARAMIS” (ARAMIS, 2004), developed in EU countries directly for the needs of safety report preparation according to the SEVESO II Directive.

#### 3.1. Creation of possible scenarios

It is necessary to deal with the scenarios that are:

- feasible (there is a real possibility of scenario occurrence) in the course of operation of the LNG storage facility,
- feasible by interaction with the surroundings (e.g. severe road traffic accident),
- highly improbable, but theoretically possible, when the consequences would be extremely serious,
- intentional damage to the installation with a view to restricting the functions (sabotage) or endangering the surroundings (act of terrorism).

Common safety and security documentation covers merely scenarios (a) and (d). For these types of scenarios, we are able to determine the probability of scenario occurrence according to the intensity of failure. For example Table 2 shows collected data where a safety valve either fails to open when required, leading to overpressure and failure of the system, or alternatively opens when unwanted, giving a release. Such failures could give a feasible release in operation of the facility.

**Table 2**

Intensity of safety valve failures according to (Red Book, 1997) showing lower and upper bounds

Component and failure mode		Mean ( $\text{h}^{-1}$ )	LB ( $\text{h}^{-1}$ )	Median ( $\text{h}^{-1}$ )	UB ( $\text{h}^{-1}$ )
3.6	Safety valve, spring operated				
3.6.1	Fails to open	6.2E-08	3.3E-09	3.3E-08	3.4E-07
3.6.2	Spurious opening	8.6E-07	2.1E-07	1.1E-06	5.5E-06
3.7	Safety valve, pilot operated				
3.7.1	Fails to open	4.8E-07	1.0E-08	1.3E-07	1.8E-06
3.7.2	Spurious opening	4.4E-06	8.6E-07	5.6E-06	3.6E-05

Notes:

Mean value: select highest value from arithmetic and geometric means.

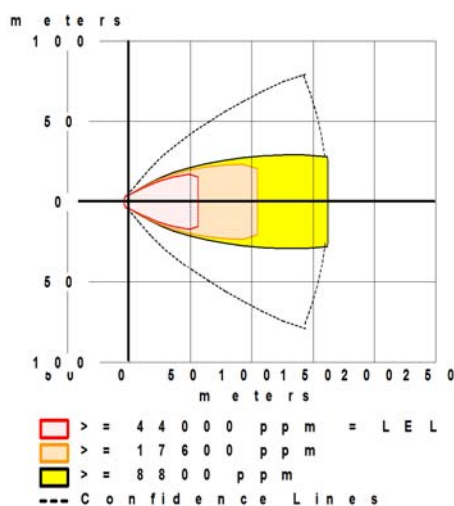
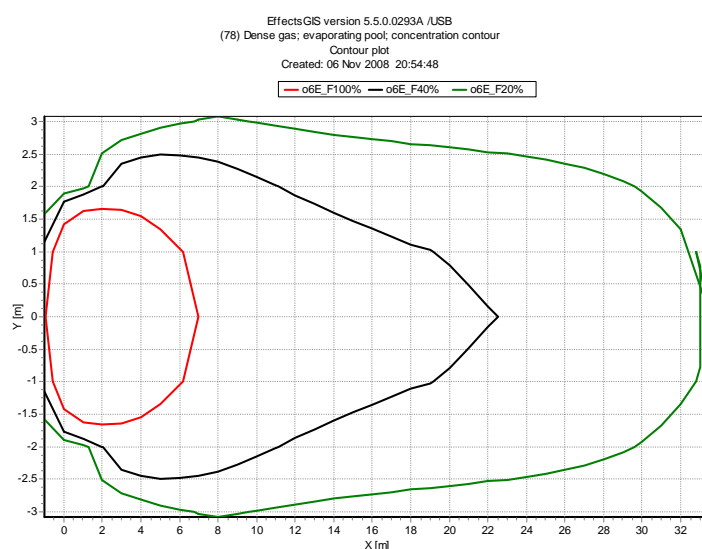
LB Lower bound: select lowest lower bound from arithmetic and geometric lower bounds.

UB Upper bound: select highest upper bound from arithmetic and geometric upper bounds.

Median value: calculated by using lognormal function

### 3.2. Results of modelling

For the detailed modelling of releases of hazardous materials and consequences of fires, explosions and toxic cloud propagation, a whole series of computer programs can be used. Some of the best known of these are ALOHA, RMP Comp, SAFETI, PHAST, EFFECTS, DAMAGE, CHARM. In addition the programs ROZEX and TerEx were developed in the Czech Republic. For a case study involving the modelling of hazardous areas after an LNG release, the programs ALOHA, EFFECTS and TerEx were selected. Examples of graphic outputs of these programs are presented in the following figures (see Fig. 1– 3.). The program EFFECTS makes it possible to represent several scenarios in one diagram.

**Fig 1.** Example of results of program ALOHA

[fig2.tif]

**Fig. 2.** Example of results of program EFFECTS

ALOHA and EFFECTS are well-known and recognised modelling software, but take too long to set up to be of use in modelling an actual incident. TerEx was selected as representative of those tools primarily intended for application in dealing with incidents, for the purpose of quick determination of hazardous zones with the minimum of required input information.

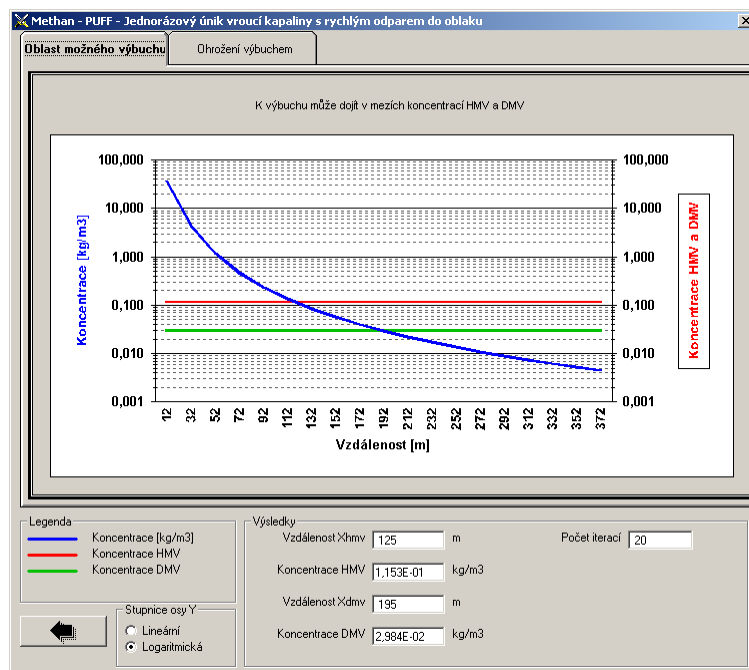


Fig. 3. Example of results of program TerEx

For scenarios of type (a) we considered the possibility of release from the liquid storage tank itself, and from the vaporiser and from the flexible piping system used to fill the tank.

Releases were considered from:

1. The largest safety valve on the tank
2. The largest safety valve on each vaporiser
3. The safety valve on the fill pipe
4. The standard safety valve on the filling module
5. Blowing through the valve DN40 from the vapour space
6. An LNG release from the filling hose

For all the 6 specified sources of releases, relevant representative scenarios of possible LNG release under the following conditions were determined:

- from the meteorological conditions two basic situations were selected:  
stability class D, wind velocity of 5 m/s, air temperature of 15°C ( representing the most frequent conditions throughout the year)  
and stability class F, wind velocity of 1.7 m/s, air temperature of 0°C ( representing an inverse situation, and thus the worst conditions for dispersion);
- in order to consider suitable locations for flammable gas detectors, hazardous zones for 20% and 40% lower flammability limits (LFL) and especially for the concentration of 100% lower flammability limit were modelled for the determination of a zone endangered by flash type fires;
- points of release were specified to occur at the height of 5 m (or 9 m) above the ground because all operational releases into the atmosphere (safety and depressurizing valves) were taken into the vent pipes, the outlets of which were about 5 m above the ground. In these cases, a release of LNG in gaseous form only is expected in contrast to a two-phase spill which occurs in damage to pipes and/or pressure vessels.

Table 3 shows summary results for six basic scenarios and enables partial comparison of results of hazardous zones for the concentration of 100% LFL.

**Table 3**

An overview of results of modelling of LNG hazardous zones

Scenario	Condition (stability class)	Evaluated parameter (hazardous zone) [m]		
		ALOHA (100% LEL)	EFFECTS (100% LEL)	TerEx (100% LEL)
1	D	30	-	35
	F	41	-	37
2	D	0	-	21
	F	0	-	22
3	D	42	-	46
	F	56	-	49
4	D	11	-	6
	F	11	-	6
5	D	30	-	46
	F	41	-	50
6	D	22	-	N/A
	F	19	-	N/A

*Note: a hyphen means that the program has not determined any relevant concentration*

*N/A – inapplicable for the given program*

From the results of this modelling, it was possible to define hazardous areas in which a flash fire might occur within the first tens of meters from the equipment. The outlets of safety valves and vent pipes being from 5 to 9 m above ground thereby reduce the chance of the flammable gas cloud meeting a source of ignition. In spite of this, it is recommended that ignition sources are rigorously excluded up to 50 or 100 m, remembering that several tons of LNG may be released through the safety valves in a relatively short time.

Of the selected software, the American program ALOHA proved to be the best, making it possible to model a direct release of LNG and also a potential release through a potential hole in a tank or pipe. ALOHA is widely used by professionals, although it is regarded as conservative in the literature. The well-respected Dutch program EFFECTS did not determine any hazardous concentration in the vicinity of the point of release at the heights of 5 or 9 m above the ground. The Czech program TerEx is designed especially for modelling in extraordinary situations and thus does not make it possible to set input data in detail. Despite this, results obtained for direct LNG releases are comparable with those of program ALOHA.

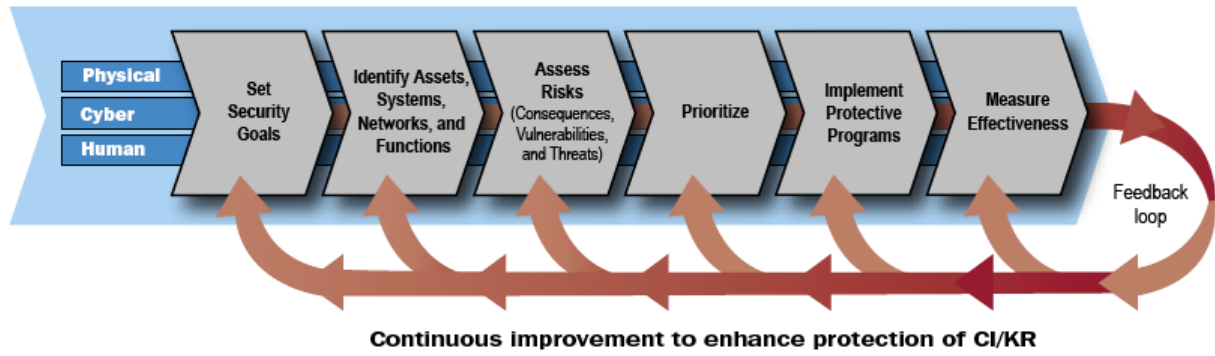
### 3.3. Other possible scenarios

Scenarios of type (b) also require taking into account the synergistic effects of various incidents that, either originate elsewhere and spread to the LNG facility (Senovsky, 2007), or on the contrary spread from the LNG plant to units nearby.

Scenarios of the type (d) are also non-traditional, because they require, in addition to the modelling of consequences of an intentional act, the modelling of the manner of its initiation as well – in the sense of requiring access to the installation in the extent necessary to commit of the act, it means the modelling of entrance and taking into account the influence of protective measures on the degree of success of the attack.

The USA has been especially concerned with programmes for critical infrastructure asset protection, with work on methodologies for the assessment of vulnerability of specific installations. The basic plan for critical infrastructure protection in the USA was published under the title National Infrastructure Protection Plan (NIPP, 2006, 2009). This plan is to be used for the coordination of activities across the sectors of critical infrastructure so that the efforts of the US Federal Government may be used as effectively as possible.

The basis of the plan is the risk management framework, see Fig. 4.



**Fig. 4.** The NIPP risk management framework (adapted from (NIPP, 2009))

#### 4. Methodology for the evaluation of national monuments and icons

As part of the inputs to the NIPP, a report was produced on National Monuments and Icons (NMI, 2007). This suggested an index for quantifying the effect of a major attack on those public places and items counted as national monuments and icons. This could then be used to rate the relative importance and thus the resources which should be applied. The following equation gives the Criticality C (1).

$$C = 2 \cdot C_{\text{type}} + C_{\text{casualties}} + C_{\text{economic impact}} + C_{\text{length of outage}} + C_{\text{impact on other sectors}} + C_{\text{environmental impact}} \quad (1)$$

The first term, type, means the significance of a monument, and warrants a little explanation. Points are allocated according to the following hierarchy.

- 1) national critical – unique, widely recognized both in the USA and internationally, symbolic of the USA
- 2) national significant – recognized national monument as symbol of the USA
- 3) regional critical – unique, widely recognized on a regional level
- 4) local significant – generally recognized and significant on a local level.

An example of type 1 would be the Statue of Liberty. By its very existence it is supposed to have a value to the morale of the United States. It is therefore reckoned that its destruction would have a similar negative effect and therefore the effect of its total loss would diminish morale by twice this value. Hence the first term has a factor 2.

The number of casualties is estimated on the basis of normal (average) number of visitors that could be killed or wounded in the monument and in the near surroundings. The economic impact means the quantification of direct and indirect loss (limitation on the number of tourists, costs of emergency response, costs of environmental damage mitigation). The length of outage means the length of time for which the monument will not fulfil its function, i.e. the time necessary to resume normal operations. This may mean rebuilding or even recreating some feature. The impact on other sectors is a measure of impact of outage of the element on other sectors (e.g. transport – monument will not be accessible, any reason to arrive will not exist, and others).

Finally, the environmental impact makes it possible to measure direct as well as indirect damage to the environment and also costs of environmental remediation.

The higher the calculated value, the greater is the consequence of damage to or destruction of the monument. This index can thus be used for the setting of security investment priorities. Nevertheless, it is necessary to realize that this index does not measure the effectiveness of already existing security measures; this effectiveness must be then assessed separately as likelihood of successful attack (2).

$$L_A = 1 - S_E \quad (2)$$

where  $L_A$  likelihood of successful attack  
 $S_E$  effectiveness of protective measures

The effectiveness of protective measures can be given a value (probability) from Table 4.

**Table 4**

Effectiveness of protective measures (Senovsky, 2008)

Effectiveness of protective measures	Security system characteristics	Value
Fully effective (very high)	The security system represents a significant obstacle to achieving the objectives of attack scenario.	0.9
Effective (high)	The system represents an obstacle to achieving the objectives of attack scenario; the overcoming of this obstacle will require great effort.	0.7
Somewhat effective (moderate)	The system represents an obstacle the overcoming of which requires moderate effort.	0.5
Minimally effective (low)	The system represents an obstacle the overcoming of which requires minimal effort.	0.3
Ineffective (very low)	The system does not put obstacles that would prevent achieving the objectives of attack scenario.	0.1

The value of risk  $R_{TS}$  can be then calculated as follows (3):

$$R_{TS} = C \cdot L_A (1 - S_E) \quad (3)$$

Again, when applying to more monuments (and other objects), a list arranged according to risks is generated; it can serve the setting of priorities of investment in protection or the modification of operating rules of objects evaluated.

The use of this method also avoids, to a certain extent, a problem of calculability – because the value of monuments is often given as “incalculable” and therefore no value can be given. If so, it is very difficult to determine the objective significance of a monument, which necessarily must lead to uncertainty in deciding what is an appropriate level of resources to spend on security.

However, it must be pointed out that the NMI report does not give a method for assigning values to the terms in the equation. This is to be developed.

## 5. Application to LNG Facilities

It is here suggested that this method is sufficiently general to be applied to LNG storage facilities. In fact it is probably easier, since imponderables such as national morale need not be considered, and methods such as the modelling given above can be used to estimate casualties. In such a case, the formula (1) can be modified as follows (4):

$$C = C_{\text{size}} + C_{\text{casualties}} + C_{\text{economic impact}} + C_{\text{length of outage}} + C_{\text{impact on other sectors}} \quad (4)$$

The type of monument can be replaced by the significance (size) of an installation

- 1) critical – large storage facilities with strategic reserves
- 2) national significant – putting out of service will affect LNG supplies on a national level
- 3) regional critical – merely regional influence
- 4) local significant – merely local influence.

It is suggested that the size factor can be derived from the asset value, which is generally known (and no factor of 2 would be required). However, this should be the replacement cost, rather than the construction cost. As this is in monetary terms, it would be relatively simple to deal with the other terms on a cost basis as well. This has the advantage that it is easy to use in cost-benefit studies.

The number of casualties can be derived from the estimated number of casualties as a result of critical failure of installation (the worst scenario). To convert this to a monetary value we can use the Value of a Statistical Life (VoSL) as is used in road traffic calculations (e.g. Wijnen et al, 2009). This is typically of a few million euros or dollars per life with 10% for non-fatal injuries. The economic impact and also the value of lost production due to outage and the impact on other sectors can be estimated. The environmental impact has been omitted as it will generally be negligible in comparison with other effects. If the methane is burnt then the ultimate environmental impact is the same as if it had been used. If it is vented, it makes a small contribution to greenhouse gas effects.

The original method sought to make a list of monuments and their level of criticality regardless of owners. The modified methodology can serve the same purpose, i.e. making a list of LNG storage facilities, taking into account the degree of their protection and the degree of significance across the whole sector. In such a case, some public authority should have the responsibility for making the list.

In addition, companies could use the technique to rate their LNG facilities in terms of these risks and to consider the need for investment in protective measures.

## 6. Conclusion

The aim of this paper was to draw attention to risks associated with the increased use and hence storage of LNG as a fuel, and thus also potential element of critical infrastructure. For operators of these facilities, hazardous zones around various sources of releases of natural gas can be determined. From the point of view of government, LNG storage facilities must be protected against intentional damage (sabotage, terrorist attack) and these issues taken into account in planning land use and energy infrastructure.

The criticality evaluation proposed for national monuments has been modified and is suggested as a method for quantification of the hazards of LNG installations, considered in the light of potential industrial accidents and also deliberate attacks.

Hazards can only be controlled if they are recognised and evaluated. This paper has shown how such an evaluation can be applied to LNG facilities.

## Acknowledgements

A part of this work was written in the framework of dealing with the grant project of Ministry of the Interior of the Czech Republic under number VD20062010A06 titled "Research into New Principles and Methods in the Framework of Civil Protection".

## References

- ARAMIS (2004) Accidental Risk Assessment Methodology for Industries in the framework of the SEVESO II directive, User Guide, contract number: EVG1-CT-2001-00036, December 2004, <URL: <http://aramis.jrc.it>> [cit. 2008-10-28].
- Bernatik, A., Zimmerman, W., Pitt, M., Strizik, M. Nevrlý, V. and Zelinger, Z. (2008). Modelling accidental releases of dangerous gases into the lower troposphere from mobile sources, *Proc. Safety and Env. Protection*, 86/B3, 198-207.
- NIPP (2006) National Infrastructure Protection Plan, DHS: 2006, 196 pages.
- NIPP (2009) National Infrastructure Protection Plan [on-line] Available from WWW <URL: [http://www.dhs.gov/xlibrary/assets/NIPP\\_Plan.pdf](http://www.dhs.gov/xlibrary/assets/NIPP_Plan.pdf)> [cit. 2010-07-23], DHS:2009, 188 pages
- NMI (2007) National Monuments and Icons - Critical Infrastructure and Key Resource Sector-Specific Plan as input to the National Infrastructure Protection Plan [on-line]. Available from WWW <URL: <http://www.dhs.gov/xlibrary/assets/nipp-ssp-national-monuments-icons.pdf>> [cit. 2008-02-10], 74 pages.
- Planas-Cuchi, E., Gasullab, N., Ventosab, A. and Casal, J. (2004) Explosion of a road tanker containing liquefied natural gas, *J. of Loss Prevention in the Proc. Ind.*, 17, 315-321.
- Purple Book (1999) Guidelines for Quantitative Risk Assessment (Purple Book CPR 18E). Committee for the Prevention of Disasters, The Hague.
- Raj P. K. (2006) Where in a LNG vapor cloud is the flammable concentration relative to the visible cloud boundary? *NFPA Journal*, May/June 2006.
- Red Book (1997) Methods for determining and processing probabilities 'Red Book' CPR 12E, Committee for Prevention of Disasters, The Hague.
- SNL (2004) Guidance on Risk Analysis and Safety Implications of a Large Liquefied Natural Gas (LNG) Spill Over Water. Sandia National Laboratories, Albuquerque, New Mexico 87185 and Livermore, California 94550.
- Senovsky, P. (2007) Statistics of accidents in industrial zones in years 1997 – 2004, *Transactions of the VSB – Tech. Univ. Ostrava, Safety Engineering Series*, 1, 73-80.
- Senovsky, P. (2008) Methods of the Critical Infrastructure Assets Risk Analysis, *Spektrum SPBI*, 1, 8-10. ISSN: 1211-6920
- Wijnen, W., Wesemann, P., & de Blaeij, A., (2009) Valuation of road safety effects in cost-benefit analysis, *Evaluation and Program Planning*, 32, 326-331